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A CFD investigation of the effect of particle sphericity on wellbore cleaning efficiency during oil and gas drilling

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Abstract

In all drilling operations in the oil and gas industry, the generation and eventual distribution of formation rock cuttings along the wellbore constitutes a major concern to operational feasibility and profitability. The nature of the annular geometry/wellbore trajectory, rheological properties of the non-Newtonian carrier fluid and physical properties of the cuttings are also very important to consider, particularly in the design stage. Cuttings encountered in practical operations are hardly of a perfectly spherical geometry; however, the ease of mathematical description due to this simplifying assumption is prevalent in most CFD modelling studies. This decreases the accuracy of simulated flow behaviour as far particle-particle and particle-fluid interactions are concerned. We address this challenge by modifying the Syamlal-O'Brien (SO) interphase exchange coefficient in the Eulerian-Eulerian model. This modification yields a better representation of the actual flow dynamics during cuttings transport. Our results show increased transport velocity of non-spherical particles compared to particles of perfectly spherical shape. The relatively complex wellbore geometry (in deviated drilling) considered reveals a key finding: there is greater particle deposition at the inclined-to-vertical (upper) bend, relative to other sections in the CFD flow domain.

Keywords: Computational Fluid Dynamics (CFD), sphericity, drag, drill cuttings.

1. Introduction

It is vital to understand the flow behaviour of drill cuttings carried by a non-Newtonian fluid in an annular geometry for successful design, efficient operation, and optimisation of the drilling process (Gerogiorgis et al, 2015). Drillers often control variables such as the penetration rate, fluid velocity and inner pipe rotation to obtain the best possible transport conditions; however, the application of advanced CFD methods for flow prediction guarantees better informed decisions. Although several experimental (Han et al, 2010; Osgouei, 2010) and computational (Rooki et al, 2015; Epelle and Gerogiorgis, 2017) efforts have sought to understand the impact of these factors on the overall transport efficiency, a widely recognised difficulty in particle transport modelling that has not been adequately addressed is the concept of particle sphericity. The assumption of perfectly spherical particles in most CFD models could yield inaccuracies in the predicted cuttings transport efficiency. In this work, this challenge is addressed by accounting for the particle sphericity as a means of increasing modelling accuracy. A modified interphase momentum exchange coefficient is implemented to better capture the particle-fluid interactions using the Eulerian-Eulerian model; thus, providing further insight into the actual dynamic particle behaviour during wellbore drilling and cleaning.

2. Drag Modification

Very few empirical correlations exist for the drag coefficient on a non-spherical single particle as well as multi-particle suspension systems. They are usually formulated either from experiments or Direct Numerical Simulations. However, our modification of the Syamlal-O'Brien drag model involves a re-definition of the particle diameter (in terms of the sphericity) in the interphase exchange coefficient. A direct application of the sphericity to the exchange coefficient ensures the particle shape is considered at conditions of high particle concentration (Gidaspow, 1994, Sobieski, 2011). The relative ease of implementation of this modification (Eq. 2 & 5) in the SO model influenced our choice of model relative to that of Gidaspow. Essentially, the need of a switch/blending function to ensure a smooth transition between conditions of high and low particle concentration is not necessary when using the SO model.

$$K'_{sl} = \eta K_{sl} \quad (1) \quad \text{Re}_s = \frac{\rho_l d_s |\vec{v}_s - \vec{v}_l|}{\mu_l} \quad (6)$$

$$d_p = \psi d_s \quad (2) \quad A = \alpha_l^{4.14} \quad (7)$$

$$\eta = \frac{1}{\psi} \quad (3) \quad C_D = \left(0.63 + \frac{4.8}{\sqrt{\text{Re}_s / v_{r,s}}} \right) \quad (8)$$

$$K_{sl} = \frac{3\alpha_s \alpha_l \rho_l}{4v_{r,s}^2 d_s} C_D \left(\frac{\text{Re}_s}{v_{r,s}} \right) |\vec{v}_s - \vec{v}_l| \quad (4) \quad \begin{array}{l} \text{for } \alpha \leq 0.85 \\ B = 0.8\alpha_l^{1.28} \end{array} \quad (9)$$

$$K'_{sl} = \frac{3\alpha_s \alpha_l \rho_l}{4v_{r,s}^2 d_p} C_D \left(\frac{\text{Re}_s}{v_{r,s}} \right) |\vec{v}_s - \vec{v}_l| \quad (5) \quad \begin{array}{l} \text{for } \alpha > 0.85 \\ B = 0.8\alpha_l^{2.65} \end{array} \quad (10)$$

$$v_{r,s} = 0.5(A - 0.06 \text{Re}_s + \sqrt{(0.06 \text{Re}_s)^2 + 0.12 \text{Re}_s (2B - A) + A^2}) \quad (11)$$

In this CFD model summary, K_{sl} and K'_{sl} denote the actual and modified interphase exchange coefficients of the SO model, respectively (Fluent, 2017), v_s and v_l are the velocities of the solid and liquid phases, α_s and α_l are the volume fractions of the solid and liquid phases, and ρ_s and ρ_l are the solid and liquid phase densities, respectively. Moreover, η is the drag modification factor, ψ is the particle sphericity (the ratio of the surface area of a sphere with the same volume as the particle, to the surface area of the actual particle), d_s is the volume-equivalent diameter (the diameter of a sphere having the same volume as the non-spherical particle), d_p is the modified particle diameter, Re_s is the relative Reynolds number, $v_{r,s}$ is the solid phase terminal velocity, μ_l is the liquid phase viscosity, and C_D the drag coefficient as per the definition of Dalla Valle (1948).

3. Simulation Parameters and Annular Flow Geometry

Table 1. Simulation input parameters

Drill pipe diameter, d_{pipe} (m)	0.113
Wellbore diameter, d_{wb} (m)	0.180
Computational length, L (m)	2.340
Cuttings diameter, d_s (m)	0.002 and 0.008
Cuttings density, ρ_s (kg.m ⁻³)	2800
Sphericity, ψ	0.5, 0.75, 1.0
Drilling mud composition	0.5% CMC Solution
Drilling mud density, ρ_l (kg.m ⁻³)	1000
Consistency index, K (Pa.s ^{n})	0.5239
Flow behavior index, n	0.60
Fluid circulation velocity, v_l (m.s ⁻¹)	0.8
Cuttings inlet velocity, v_s (m.s ⁻¹)	0.5
Flow regime	Laminar – Unsteady state
Drill pipe rotation, Ω (rpm)	100
Hole eccentricity, e	0.6

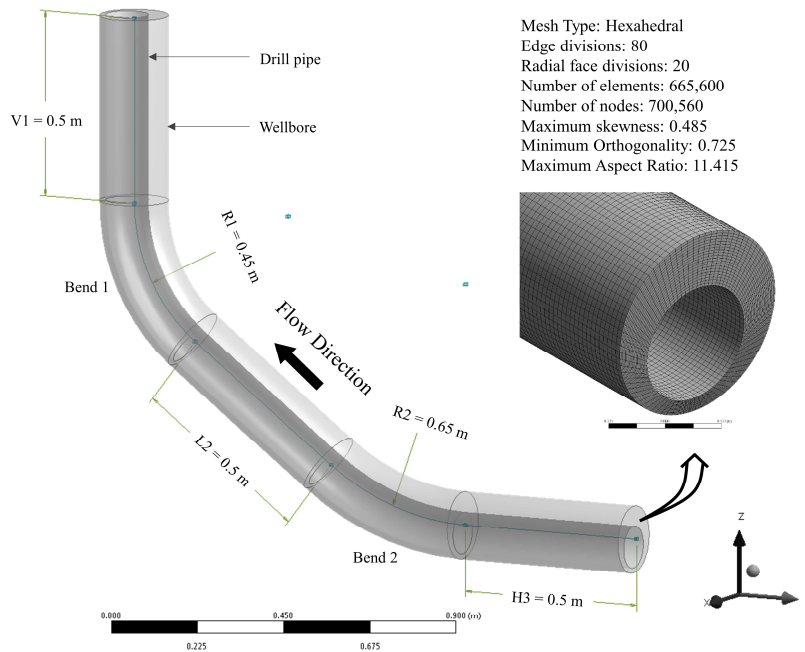


Figure 1. Dimensions of annular flow geometry with mesh properties adopted.

Transient simulations were run using the finite volume formulation with a time step of $5 \cdot 10^{-4}$ and a tolerance factor of 10^{-4} in the Ansys Fluent solver (17.1). Statistical averages of flow properties were performed over the entire converged time steps. Total simulation run time was approximately 8 days using the University of Edinburgh's high performance computing facility (Eddie mark 3 – Scientific Linux 7 Operating System)

with 32 CPU cores (2.4GHz Intel®-Xeon® CPU processor) and 64GB of RAM. The geometry is shown in Figure 1.

4. Results and Discussion

The particle velocity, pressure drop and volume fraction profiles averaged over the entire flow domain for a simulation period of 5 seconds are shown in Figure 2.

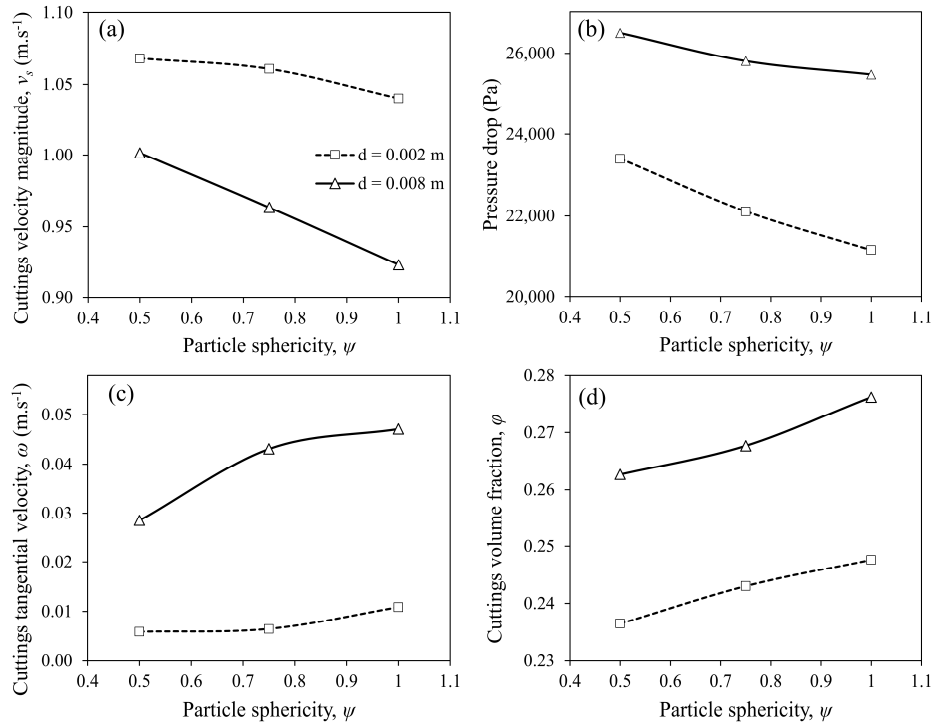


Figure 2. Cuttings velocity, pressure drop and volume fraction for variable sphericity.

It has been shown that non-spherical particles undergo a secondary oscillatory motion when transported in a fluid (Mandø et al. 2007). This tends to reduce its settling velocity compared to perfectly spherical particles (Byron, 2015). The higher settling velocity of spherical particles in the partially inclined geometry considered, is the most probable reason for the increased deposition (volume fraction – Figure 2d) and the reduced velocity in the direction of bulk flow (Figure 2a). Furthermore, spherical particles will tend to roll against the flow direction during transport; the results obtained show that these combined phenomena exhibited by spherical particles, are superior to the frictional resistance posed by the non-spherical particles (due to increased contact area).

Cuttings with diameter of 0.002 m generally travel faster in the annulus than those of 0.008 m (Figure 2a). However, larger particles exhibit stronger tangential motion compared to the smaller particles (Figure 2c). This occurs as a result of the rotating drillpipe which has a higher impact on spherical particles compared to non-spherical particles (Figure 2c). Spherical particles will more readily rotate along the axis of the drillpipe compared to non-spherical particles with a more chaotic flow character.

Interparticle collisions of non-spherical particles coupled with the increased drag forces are the most likely reasons for the higher pressure drop noticed with the non-spherical particles (Figure 2b). Additionally, larger particles will require more transport energy; hence the higher pressure drop and volume fractions (Figure 2d) observed. The impact of drillpipe rotation on the larger particles is further demonstrated in Figure 3 (d-f) and Figure 4. While the 0.002 m particles tend to settle at the lower section of the eccentric annulus, larger 0.008 m particles clearly experience an asymmetric deposition pattern.

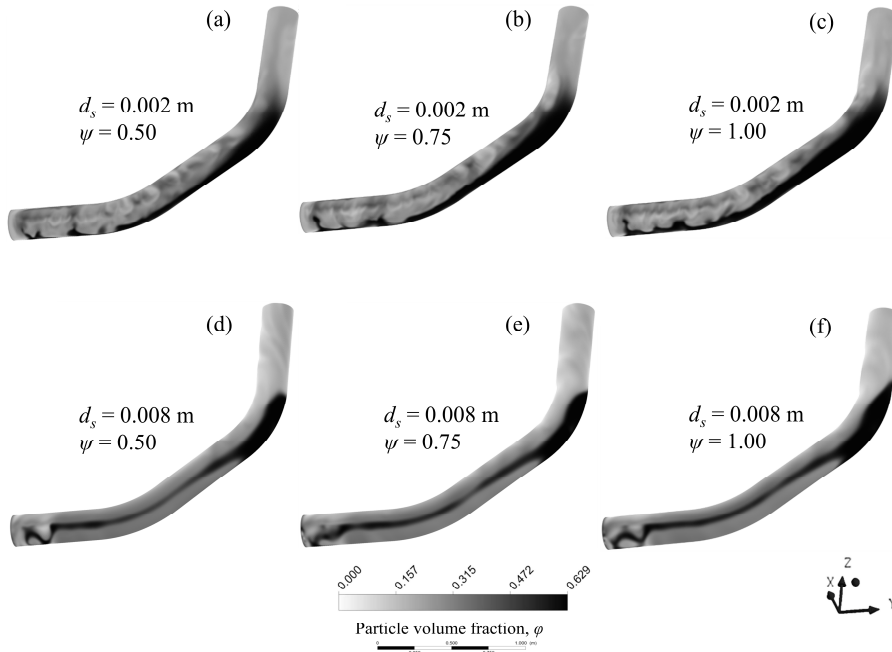


Figure 3. Impact of particle diameter and sphericity on solid volume fraction at bends.

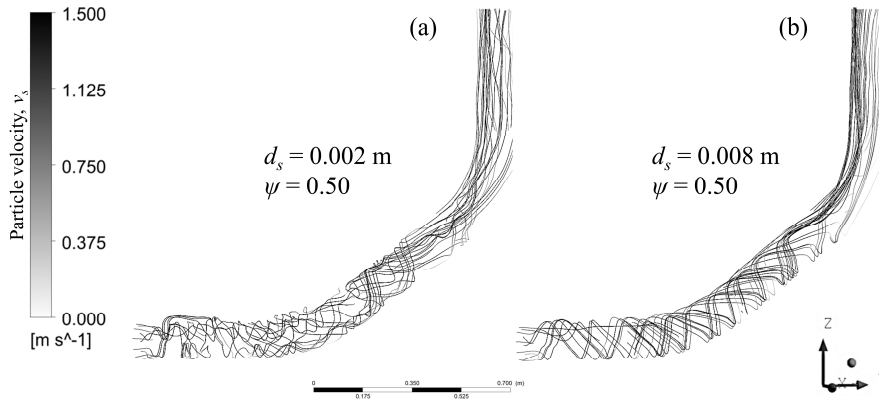


Figure 4. Annular flow velocity streamlines for two particle sizes at given sphericity.

The particle streamlines shown in Figure 3 (a & b) indicate that the impact of drill pipe rotation on particle motion in the vertical section of the annulus is much lower compared to the inclined and horizontal sections respectively. This effect was noticed for all particle sphericities considered. Furthermore, this reduced impact of drillpipe rotation due to the transition in the annular geometry coupled with the eccentric configuration of flow are the major reasons for increased particle deposition noticed around the bend (inclined-to-vertical) compared to other areas of the flow domain.

5. Conclusions

By incorporating the particle sphericity into the interphase momentum exchange coefficient of the Syamlal-O'Brien model, we have studied the impact of particle shape on the multiphase flow of drill cuttings in irregular annular geometries. The obtained results show a 5% reduction in cuttings volume fraction between particles of lowest sphericity (0.5) and perfectly spherical particles for both particle diameters considered. As far as the cuttings transport velocity is concerned, the shape of the particle is more influential on larger cuttings compared to smaller-sized cuttings. We also discover that the inclined-to-vertical (upper bend) is the most susceptible location for particle deposition. Drillpipe rotation is seen to have a more pronounced effect on larger particles, especially in the horizontal and inclined regions of the annulus. In the vertical section, the effect of rotation is low; we infer that this phenomena, alongside increased gravitational resistance are the main reasons for increased deposition in the upper bend.

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